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A Simple Analog BLDC Drive Control for Electro-Mechanical Energy Storage System

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Abstract

Electro-Mechanical Batteries have important advantages compared with chemical batteries. High speed, slotless, external rotor, BLDC machines are used in these systems as Motor/Generator. It is used for converting the electrical energy to the rotational kinetic energy and vice versa. A bidirectional, variable frequency, variable amplitude, three phase BLDC drive needs for its operation in charge and discharge state. Generally, microprocessors are used for their control. But they are complex and expensive. In this paper, limitations, considerations, design and construction of a simple analog control circuit presents. Experimental results are verifying the design proses.

Keywords: Flywheel; Electromechanical battery; energy storage; BLDC; Drive; Bidirectional Converter

1. Introduction

Flywheel energy storage systems or Electro-Mechanical Batteries (EMBs) are introduced by Maryland University [1] and NASA [2] in 1970s. Recently, they are most commonly used in Low Earth Orbit (LEO) satellites. Nano/micro satellites are usually included in LEO satellites, which rotate around the earth from some minutes to a few hours. Although the development of chemical batteries technology, the most critical part of these satellites, is their energy storage system, their life is limited by fast charge/discharge rating in such applications [3].

Rotational kinetic energy is stored in a high-speed flywheel in EMBs. The advantages of EMBs are presented in [1]-[5]. Unlimited charge/discharge cycle as well as the satellite lifetime, higher efficiency, higher energy density, higher discharge depths, thermal independency and their usage in attitude control of satellite can be mentioned as some of these advantages. Instruction for design and optimization of flywheel to achieve lower stress and weight for space applications are presented in [4], [5].

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The most important part of an EMB is the electrical machine, which is used as Motor/Generator for energy conversion. Synchronous permanent magnet Brushless DC (BLDC) machines are mostly used in EMBs because of having high torque to weight ratio, low rotor losses, high efficiency and brushless ness. So, they are introduced and proposed to be used in EMBs in [5]. Design and optimization of electrical machine is given in [6] and verified with finite element method simulations.

Energy is stored as rotational kinetic on a flywheel. So, rotational speed of flywheel varies between wide ranges. This cause the electrical machine’s frequency and each phase amplitude to de variable during charge and discharge continuously. Control of such an inverter can be done using a microprocessor in the earthly applications.

But in the space latch up is a common problem in these kinds of ICs during space radiation [7]. Many CMOS circuits are sensitive to latchup from heavy ions, and latchup is one of the major considerations when CMOS devices are evaluated for space applications. Radiation-induced latchup has been studied for many years [8]-[11], but it remains a difficult problem in actual circuits because latchup sensitivity inherently depends on the layout and distribution of contacts, power and ground within complex circuits [8], [9]. The gain of the parasitic bipolar transistors that form potential latchup paths is nearly always high enough so that latchup can potentially occur.

Although sufficient protections are considered in circuit design for space application, latchup reduces the total reliability of satellite considerably during its accessibility in the space. So, a simple analog controller is preferred to use instead microprocessors.

In this paper, Design procedure of a bidirectional variable frequency and voltage drive including a bidirectional converter (BDC), variable voltage and frequency inverter beside a simple analog control circuit is presented. To this aim, electromechanical battery operation concepts will discuss in section II. Proposed circuit is given in section III. Experimental construction and its results are given in section IV and section V is conclusion of the paper.

2. EMB Operation Concepts

Fig. 1 shows an EMB. Electrical energy converts to kinetic energy in the charge duration and flywheel speeds’ increase until maximum allowable speed which determined by mechanical limitations. Stored energy on flywheel, E_n, calculates using equation (1) [6].

$$E_n = \frac{1}{2} I_{total} (\omega_2^2 - \omega_1^2) \tag{1}$$

where I_{total} is flywheel inertia and ω_1 and ω_2 are maximum and minimum allowed flywheel speed respectively. Maximum speed of rotation is kept as high as possible for mass and volume optimization. Rotational speed kept between 20000 and 60000 rpm in satellite application [12], [13].

The most important part of an EMB is the electrical machine, which is used as Motor/Generator for energy conversion. Brushless DC (BLDC) machines are mostly used in EMBs because of having high torque to weight ratio, low rotor losses, high efficiency and brushless ness [14], [15]. The speed of flywheel is varied up to three times to achieve the proper depth of discharge [12]. In BLDC machines, voltage of output terminals is proportional to rotor speed, so, the output voltage varies more than tripled and proper DC-DC converter topology has to be selected.

On the other hand the terminal voltages and currents can be controlled using drive, or inverter, system. So, BLDC machine can be operated in motor or generator mode.

Electrical power subsystem of a satellite including EMB energy storage system is shown in Fig. 2. EMB’s drive consist a BDC and a bidirectional, three phase, variable speed and voltage inverter. Electrical energy is converted to rotation kinetic one during the charge state. So, the speed of flywheel will increase according eq. 1 and vice versa in discharge stat. the speed variation of a case study flywheel is shown in Fig. 3. It is noticeable that produced voltage is proportion with rotational speed in BLDC machine, so, Fig. 3 also shows the machine's terminal voltage variations.

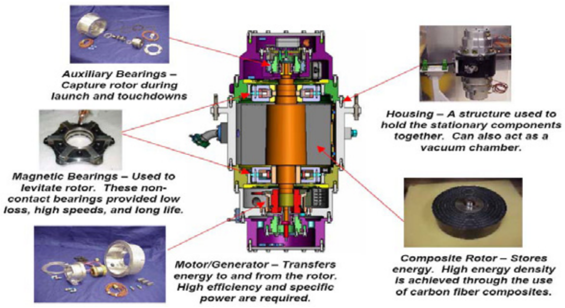

Fig. 1. An electro-mechanical battery [16].

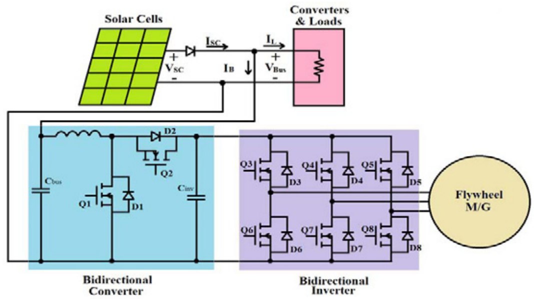

Fig. 2. Electrical power subsystem of a satellite, including EMB energy storage system.

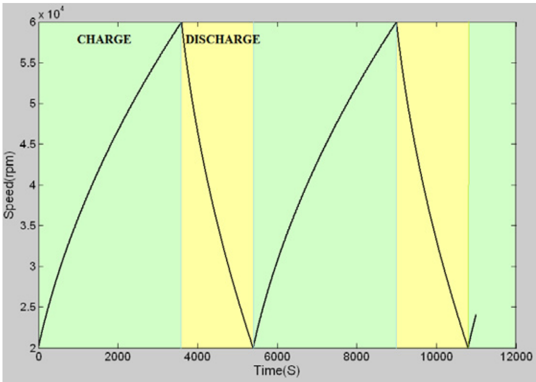

Fig. 3. Flywheel speed variations during charge and discharge.

3. Proposed Circuit

The main step in EMB's drive design is the three phase inverter which inverts the input DC voltage, V_{inv}, to a variable frequency trapezoidal waveform adequate for BLDC machine and vice versa. Q_3 to Q_8 forms inverter during charge state and D_3 to D_8 constitute a three phase full bridge rectifier during discharge state. In electrical machinery, including BLDC, produced torque will maximized when the stator field be in 90 electrical degrees with rotor field. On the other hand the trapezoidal back electromotive force, BEMF, in BLDC machine causes its easy and rotor's position independence derivation. Therefore, a simple drive can be achieved by detecting position of 90 electrical degrees between rotor and stator fields. Since stator winding is fix on the stator, this position can be defined with three hall effect sensors for three phases of machine. Finally, by distributing three hall effect sensors whit 120 electrical degrees in the start of each phase, the exact duration of each stator winding will be defined to energize. The three phase operation of BLDC drive can be divided to six parts. The state of each switch can be defined from hall effect sensors signal according table 1. The logic of this table can be achieve by three NOT and six AND gates.

Table 1. The relation between hall effect signals and switch's state

ha	hb	hc	emf_a	emf_b	emf_c	Q1	Q2	Q3	Q4	Q5	Q6
0	0	1	0	-1	+1	0	0	0	1	1	0
0	1	0	-1	+1	0	0	1	1	0	0	0
0	1	1	-1	0	+1	0	1	0	0	1	0
1	0	0	+1	0	-1	1	0	0	0	0	1
1	0	1	+1	-1	0	1	0	0	1	0	0
1	1	0	0	+1	-1	0	0	1	0	0	1

The logical schematic is shown in Fig. 4 beside MOSFET's gate drivers. It is noticeable that such a circuit is completely frequency and speed independent.

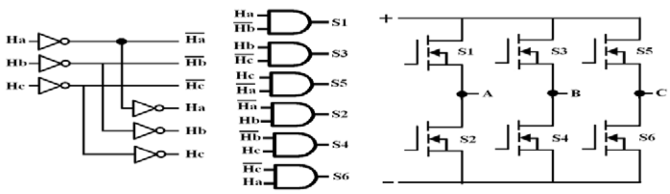

Fig. 4. The logical schematic of inverter

The three phase inverter operates in EMB charge state. In this state BLDC machine works as a motor. During discharge state BLDC machine works as a generator and the full bridge rectifier converts three phase voltage to dc.

The second part of EMB's drive is bidirectional DC-DC converter, BDC, which is interconnection between bus and inverter. It controls the current rate of charge and discharge. This work is done by controlling switching duty cycle based on maximum power point tracking, MPPT, in the input and current control at the output. It is shown in Fig. 4. It works as boost converter in the charge state and increases DC bus voltage to suitable level for BLDC machine. In discharge state it works as buck converter. It decreases and stabilizes DC bus voltage to appropriate level for loads' DC-DC converters.

Output voltage of this converter or input voltage of three phase inverter is controlled based on flywheel speed and electrical machine state (motor/Generator), from 30 to 95 volts. In the charge state, Q_1, D_2, L and C_{inv} constitute a boost converter. The input voltage of BDC is controlled based on solar cell MPPT, in charge state from 17 to 28 volts. It kept constant in discharge state at 35V based on loads' converters more efficiency. In the discharge state, Q_2, D_1, L and Cbus constitute buck converter. The control of this converter is done by a PWM IC controller (UC1843) for each direction. The boost controller IC only controls the output, EMB's, current. Its reference comes from MPPT controller which is also an analog circuit. But, controller of buck converter regulates the dc bus voltage against EMB's voltage and satellite load variation during discharge state.

4. Experimental Results

The experimental results are given here for design verification. The main problem in flywheel construction in the laboratory is the weight. Flywheel has no weight in the space. So its levitation is easy. It can easily achieve by low power magnetic bearings. The other problems in laboratory are the air dissipation. Also a perfect balancing is needed to minimize the mechanical stresses and dissipation which is too expensive for a case study prototype. So, an EMB with maximum speed of 6000 rpm is constructed. According eq. 1, in this case the weight of flywheel will be more for the same stored energy (12kg for 145kJ). Fig. 5 shows the experimental setup and Fig 6 shows the constructed prototype inverter.

Figs 7 and 8 show the voltage and current waveforms of one phase of BLDC motor in charge state and 6000rpm. As it is clear in these figures, during simple design and single pule switching control, the waveforms are different with their ideals trapezoidal one which make torque ripple. But in EMB application torque ripple is perfectly damped by the inertia of flywheel, so it do not account as a disadvantage. Fig. 9 shows the output voltage of a single phase of BLDC machinery in discharge mode at 6000rpm. Here BLDC machine work as a generator.

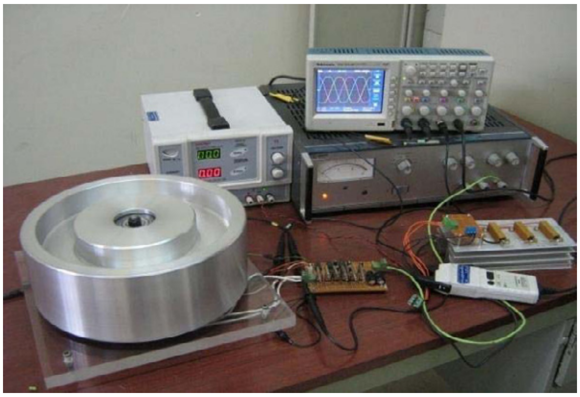
Fig. 5. The experimental setup.

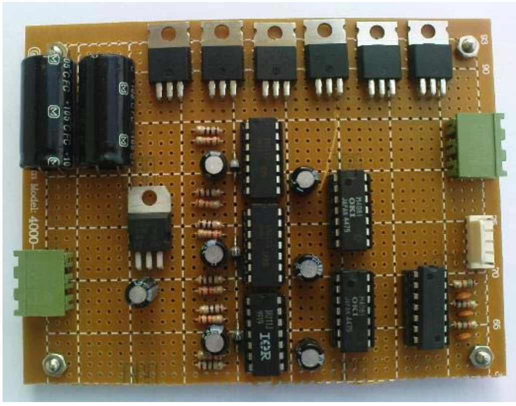
Fig. 6. Prototype inverter

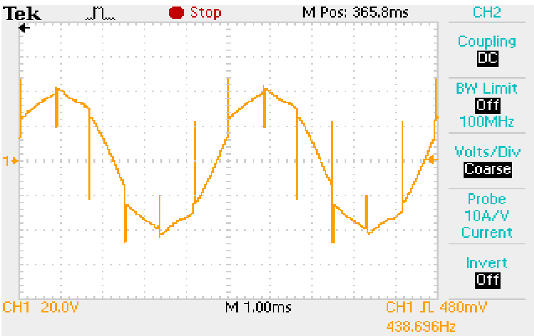

Fig. 7. Output voltage of inverter in charge state at 6000rpm

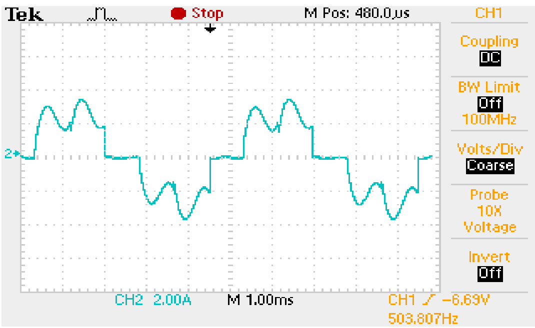

Fig. 8. Output current of a phase of inverter in charge state at 6000rpm

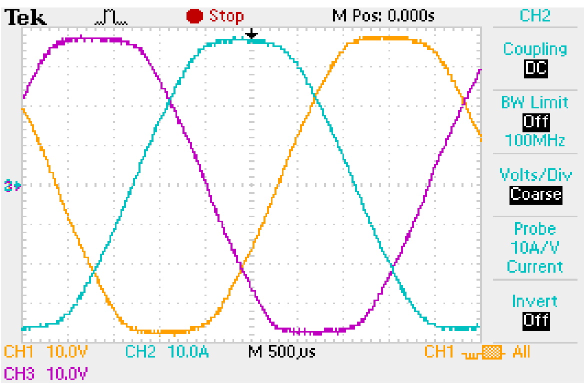

Fig. 9. input voltage of rectifire in discharge state at 6000rpm

5. Conclusion

Electro-Mechanical Batteries have important advantages compared with chemical batteries in LEO satellites. Generally, BLDC machines are used in these systems as Motor/Generator. A bidirectional, variable frequency, variable amplitude, three phase BLDC drive needs for its operation in charge and discharge state. Generally, microprocessors are used for their control. But they reduce the reliability and satellite life time during latchup phenomenon in the space. A simple analog and latchup free control circuit is presented in this paper. A prototype EMB and its drive are constructed. The designed circuit verified by prototype system.

Acknowledgements

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